

COMMENTARY

Techno-economic, environmental, and social measurement of clean energy technology supply chains

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Abstract

In addition to the criteria of reliability and cost, clean energy technologies, such as wind, solar, and batteries, need to strive to a higher standard of environmental and societal benefit along their entire supply chain. This means additional performance metrics for these technologies should be considered, such as embodied energy, embodied carbon, recycled content and recyclability, environmental impact of material sourcing, impact on land and ecosystems, materials recovery at end of life, and production through quality nonexploitive jobs with community benefit. Many commercial and emerging energy technologies have not yet been explicitly evaluated based on these environmental and social performance metrics, which presents multiple opportunities for researchers and analysts. In this paper, we review the importance and current limitations of techno-economic and life-cycle assessment models for research design and manufacturing decisions. We explore emerging manufacturing modeling options that could improve environmental and social performance and how they could be used to help guide research. Even with the deployment of low-carbon energy-generation technologies, the future of a successful clean energy transition requires collaboration between researchers, advanced manufacturers, independent standards and tracking organizations, local communities, and national governments, to ensure the financial, environmental, and social sustainability of the entire supply and manufacturing process of energy technologies.

KEYWORDS

clean energy, green manufacturing, life-cycle assessment (LCA), social sustainability, supply chain, sustainability, techno-economics (TEA)

1 | INTRODUCTION

Manufacturing and clean energy have a unique intertwined relationship. In comparison to fossil fuels, the materials and economics of many renewable energy sources depend more

heavily on volume manufacturing of technologies. As these technologies aim to reduce environmental impact, developers, investors, and consumers demand that renewable energy technologies meet sustainability objectives for their manufacturing and end-of-life management. A global drive

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for sustainability also means that the broader manufacturing sector is seeking lower-emission energy sources, a potentially virtuous circle between renewable energy and advanced manufacturing.

Many challenges and opportunities exist in defining, measuring, and achieving sustainability in manufacturing of clean energy technologies. First is reaching a common set of definitions. For this commentary, we use the triple-bottom line definition of sustainability, meaning achieving economic, environmental, and social benefit equally.

Second, while there is considerable debate over what a clean energy technology is, we define it as a technology for the production of energy that produces very low levels of emissions using a nondepletable fuel source. Here, we are further considering the subset of clean energy technologies that are mass manufactured, such as: solar photovoltaics, wind turbines, green fuels (hydrogen, biofuels), and batteries. While fitting the definition of clean energy technologies, we do not consider technologies such as geothermal, hydro, or nuclear power as mass manufactured, due to their specialized supply chains, need for quasi-customization of very large power plants, and, in the cases of small modular reactors, micro-hydro, and enhanced distributed geothermal, their status as pre-commercial technologies that are not in full-scale production.

Our scope of manufacturing supply chains is comprehensive, including raw materials, processed materials, subcomponents, final product, and circularity (Figure 1). Circularity or circular economy means the recovery of

waste materials throughout the manufacturing process and at the end of product life and their reprocessing and manufacturing into the same or different useful products.

The remaining challenge, and the topic of this paper, is defining supply chain sustainability metrics, analysis modeling of sustainability, and measuring social metrics transparently. We also briefly summarize needed research and incentives to make measurement of sustainable manufacturing possible.

2 | SUPPLY CHAIN SUSTAINABILITY METRICS

Companies of all types have stated goals regarding environmental, social, and governance (ESG) measures, and multiple approaches have emerged to support the definition and measurement of meeting these goals. In recent years, greenhouse gas (GHG) emissions have been a focus of ESG metrics, serving as a proxy for environmental impact. Beyond GHG, many other metrics have been proposed or used, such as embodied energy, recycled content and recyclability, impact on land and ecosystems from material sourcing, materials recovery at end of life, and creation of quality nonexploitive jobs with community benefit.

The Greenhouse Gas Protocol defines three source areas, but these are broadly applicable to multiple types of metrics: Scope 1 impacts from sources owned or controlled by the company, Scope 2 from purchased energy, and Scope 3 from the upstream and downstream supply

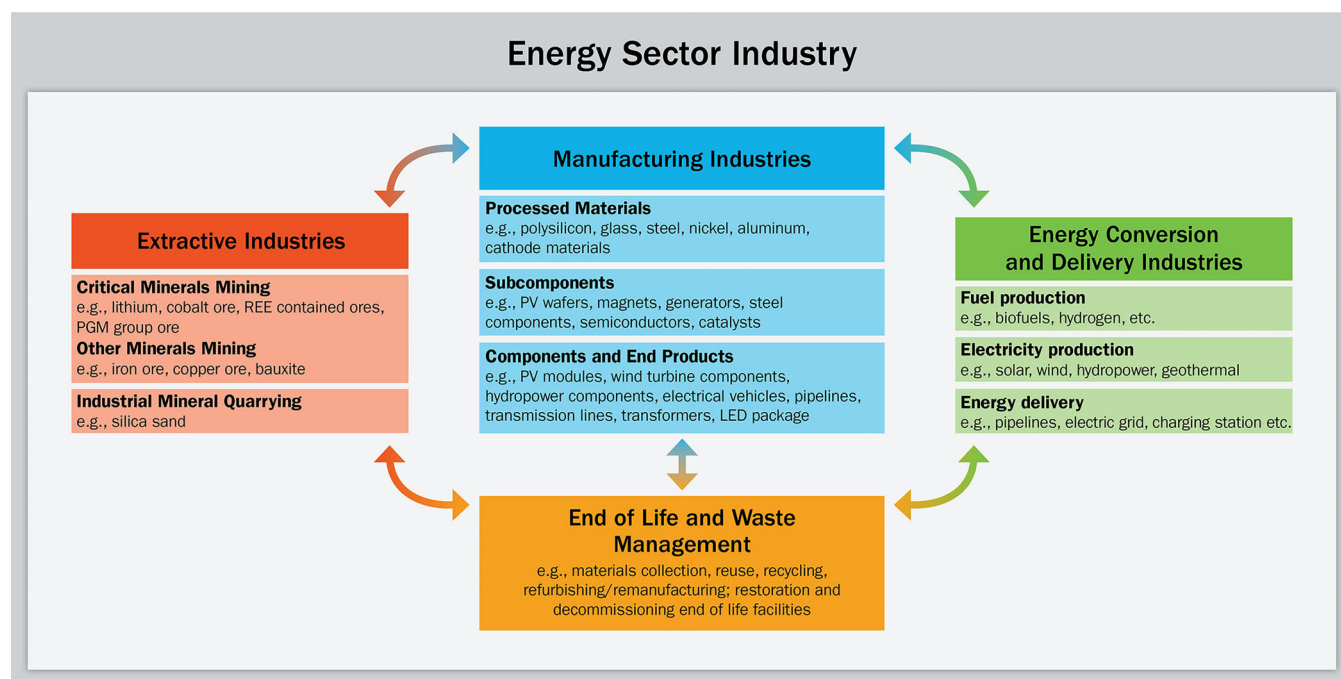


FIGURE 1 Energy sector industry (adapted from Reference [1])

chain.^[2] High-quality metrics should also meet requirements of relevance, completeness, consistency, transparency, and accuracy.^[2]

The supply chain (Scope 3) has been identified as the largest impact and most challenging to measure.^[3] Supply chains are complex, long, and variable, stretching back to basic mining of commodity materials and forward through product use and recovery at end of life, so meeting the objectives for completeness, consistency, transparency, and accuracy becomes very difficult. However, one company's Scope 3 impacts are their suppliers' or customers' Scope 1 and 2 impacts, so, in theory, greater uptake of consistent metrics and standards could improve reporting.

Yet, given the complexity of manufacturing supply chains, we believe existing metrics and standards are necessary but not sufficient. Advanced analysis models supported by measurement tools are also required, and they represent an opportunity for the research community and advanced manufacturers. Given the increased demands for ESG for clean energy technologies, we propose that their manufacturing and supply chains represent the ideal focus for demonstration of models and technologies for improved sustainability metrics.

3 | ANALYSIS MODELS FOR SUPPLY CHAIN ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY METRICS

Sustainable design can be guided using analysis models. Historically there have been two types of models used to evaluate economic and environmental impacts of a technology: Techno-economic analysis (TEA) is used for evaluating economics and life-cycle assessment (LCA) for evaluating environmental impact metrics.

TEA is an overarching method of evaluating the potential financial performance of a given technology. TEA analysis generally involves including the combination of capital costs, operating costs, material costs, utilities, taxes, research and development, and sales and administration into a parameter like minimum sustainable price.^[4] This value can then be fed into further analysis, such as levelized cost of energy. TEA generally has its strengths in being a widely accepted method of comparing technologies based on economic viability as it is integrated into the market. These analyses can also inform manufacturers of areas of potential economic constraint during scale-up.^[5] TEA is a widely applicable methodology, which can inform scientists, engineers, and investors of strengths and weaknesses in competitive markets, and this evaluation technique can be reevaluated with relative ease as more information becomes available.

However, TEA has its weaknesses. Due to its nonspecific and generalized guidelines, TEA studies can lack enough similarity to be compared due to differences in calculation methods, process clarity, assumptions, and boundary condition consistency. These analyses include a degree of uncertainty, but this is determined by the user and leaves room for ambiguity. To perform a TEA, a process model is required to calculate process and operating costs. This can result in inaccuracies during scale-up. TEA analysis also typically focuses more on economic viability of a technology at a market-scale, and in doing so does not explicitly quantify economic benefits to specific communities, or environmental or social impacts of a given technology. This can lead to the implementation of cost-effective but potentially locally harmful technologies, so TEA is done best in conjunction with other impact analysis methods.

LCA is a well-known and widely implemented method of accounting for the environmental impacts of a given technology. Most commonly, these impacts include embodied properties that sum backwards through the supply chain (for example, in photovoltaics, the first step is the energy to assemble the panel itself from glass, aluminum, and semiconductor, while the second step is energy required to make the glass, third step is the energy required to mine and refine sand for the glass making, etc.). These properties often represent the embodied energy of a technology, as in the example above, or embodied CO₂. LCAs can also include other types of environmental impact calculations such as acidification potential, or abiotic resource depletion (how might this product impact critical or sensitive materials and other natural [non-living] resources).

LCA benefits from a widely accepted set of guidelines that makes results more comparable due to consistency in boundary conditions, calculation transparency, and calculation methods.^[6] These standards, seen in ISO 14040-14 044, have benefited from increasing interest and application of LCA evaluations dating back to the 1960s. However, despite the consistency of framework and strong comparison of technologies in terms of their environmental impacts, LCA neglects to consider supply chain volatility or economics in its analysis, as well as the social impacts of compared technologies. It can also benefit from additional transparency allowing others to clearly understand and reproduce the analysis.

Integrating TEA with traditional LCA is a more complete method to compare competing technologies. With the rise in climate and ESG awareness, the lack of consideration in TEA for societal and environmental impacts is becoming a greater weakness with time. Combining TEA with LCA is a step toward solving this issue and strengthens the LCA by adding the ability to consider the potential financial performance and commercial success

of a technology as well. This aligns with the concept of triple-bottom line for industry and can help equalize demands from both stakeholders and shareholders. Indeed, industry at large has been moving in the direction of conducting LCA analysis in tandem with TEA, ensuring that under the threat of rising carbon prices and consumer concerns about emissions, technologies remain relevant and profitable. Combining LCA and TEA into a supply chain optimization model would further help with technology selection/sizing/placement, transportation, and production. While other sectors have made strides toward a model that systematically can help make decisions, further research is needed for one that is applicable to clean energy technologies.^[7]

Overall, these combined methods are complementary for technological judgment, but remain deficient in the analysis of societal impacts. These analytical processes remain prone to missing societal injustices, as analyses pursue economic success and environmental benefit. For this reason, it is important that robust assessment approaches for social impacts are developed and standardized, as LCA has been.

4 | APPROACHES FOR SOCIAL SUSTAINABILITY MEASUREMENTS

While the economic and, in part, the environmental measures and models are converging, the third line of the triple-bottom line definition of sustainability—social benefit—remains without robust models or even fully agreed-upon measures. While the integration of TEA and LCA is quite powerful in terms of understanding the impacts on GHG emissions and techno-economics, neither is individually adequate to quantify sustainability or account for aspects of social justice. Mieke et al. states, “Although sustainability represents a key factor of future production, it is not conclusively defined in order to be technically applicable.”^[8]

Recently, LCA frameworks have been expanded to include social life-cycle assessments (s-LCA), a still-developing offshoot of traditional LCA that aims to quantify how technologies impact workers, local consumers, communities, and overall societies.^[9] Guidelines have been developed by the United Nations Environment Programme, but just as traditional LCA evolved, these need to be refined as the framework is applied to diverse fields.^[10]

The generally considered pillars for s-LCA are sustainable development, human well-being, sustainable consumption and production, and corporate social responsibility. S-LCA aims to include stakeholders at all levels (consumers, workers, local communities, societies, and value chain actors). These pillars and stakeholders are then evaluated based on changes in behaviors, effects on socio-economic

processes, and overall capital (human, social, or cultural), through the more specific impact categories of human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions.

While the United Nations Environment Programme's framework gives some guidance to the process of conducting an s-LCA, the metrics for social impacts and thus the ultimate value for each category is up to interpretation—for example, is it more valuable to improve working conditions or preserve cultural heritage? Is it ethical to put values to these categories? How do these values differ among different stakeholders? These are questions that remain to be answered, but the fact that s-LCA metrics are being considered in project planning is a critical step toward a more complete and fair assessment of technologies, from an economic, social, and societal point of view.

Manufacturers can only produce trusted s-LCA information once clear guidelines, metrics, and tracking protocols are agreed upon for how to evaluate these societal impacts, as well as what impacts are most important. To reach this point, independent analyses will play a pivotal role in developing the appropriate guidelines. In doing so, methodologies and assumptions must be clearly stated and reproducible. This can help prevent industries avoiding this analysis based on confusion or inconsistency in the framework, and also prevents the manipulation of results based on vague guidelines.

5 | CONCLUSIONS AND INCENTIVES FOR INDUSTRY

Overall, there is no one-size-fits-all analysis method for evaluating the three broad sustainability metrics of economic, environmental, and social benefit. Techno-economic analysis provides financial incentives to drive research, development, and market implementation, while understanding environmental and societal impacts uses traditional and societal LCA methodologies. These three techniques form the basis of an all-encompassing technological valuation.

One of the first steps manufacturing industries of all sizes can take is to start reporting their “triple bottom line” to shareholders and stakeholders with equal weight and importance to the environmental and social lines as for the financial. Our experience is that the action of comprehensively measuring, evaluating, and reporting frequently reveals new operational approaches and markets that ultimately benefit all three measures. The use of models and tools to track robust sustainability metrics should ideally be scaled to the size of the business and incentive-based. Incentives for industry to start measuring and reporting may take the form of: increasing sales to buyers along the supply chain seeking to meet their Scope 3 goals; meeting demand for ESG from investors

and shareholders; increasing trust and social license to operate among stakeholders; and being an attractive place to work among new generations of employees. That said, national government and global participation may be necessary to ensure tracking systems are consistent, accurate, and transparent, especially across global supply chains. In the case of s-LCA, which is less developed than TEA and LCA, industry leaders will need to proactively work with employees, shareholders, customers, and community stakeholders to develop s-LCA measures that support the sustainability of the industry. Collaboration between the research community, advanced manufacturers, independent standards and tracking organizations, and national governments will be necessary to develop and use improved sustainability supply chain models and achieve the sustainability goals to reach a truly clean energy future.

AUTHOR CONTRIBUTIONS

Jill A. Engel-Cox: Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal). **Hope M. Wikoff:** Writing – original draft (equal); writing – review and editing (equal). **Samantha B. Reese:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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